

Global absorption center map of the mafic minerals on the Moon as viewed by CE-1 IIM data

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Determining the global distribution of minerals on the Moon has been an important goal of lunar science. Hyperspectral remote sensing is an important approach to acquiring minerals on the Moon on the global scale. The wavelength of the absorption band center is the key parameter for identifying minerals with reflectance spectra as well as remote sensing data. The global absorption center map of the mafic minerals of the Moon was produced for the first time with the Chang'E-1 IIM data. This map shows the global distribution of mafic minerals such as orthopyroxenes, clinopyroxenes, and olivine and even plagioclase feldspar of the Moon. The validation for some representative areas indicates that the global map is reliable and even more detailed than the results derived from Clementine-data. Moreover, our method is insensitive to the topography and viewing and illumination geometries. The global absorption band center map not only contributes to the lunar science research, but also has other implications to be further studied. Moreover, the preprocessing methods such as calibration and correction introduced in this study can be useful in other research with IIM data.

Chang'E-1, IIM, absorption band center, calibration, Moon

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1 Introduction

The rocks and minerals on the Moon recorded the past geologic processes of the Moon. Knowledge of the abundance and distribution of the rocks and minerals has led to a better understanding of the origin and evolution of the Moon [1–3]. The samples returned by six Apollo trips and three Luna programs provided invaluable information for understanding the composition of the Moon. However, the lunar sample collection is a relatively small and non-random repre-

sentation of the Moon's crust. Remote sensing, which provides a global perspective that the lunar sample collection alone cannot, is still the major means by which to acquire the compositions of the Moon. The orbital missions of the 1990s, Clementine and Lunar Prospector provided key mineralogical and geochemical data sets that extended our view of the Moon beyond what we knew from Apollo and Luna explorations to a truly global perspective [4]. In this century the new launched missions, KAGUYA, Chandrayaan-1 and LRO, provided us the global distribution of pure anorthosite [5] and corroborated the existence of H₂O or OH on the Moon [6], which throws light on our understanding of the Moon.

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Reflectance spectra of minerals contain absorption features that are diagnostic of the composition and crystal structure of the transition metal and their host minerals. The wavelength of the absorption band center is the key parameter for identifying minerals with reflectance spectra as well as remote sensing data. Due to the large bandwidth and discontinuous spectra, multispectral remote sensing such as Clementine cannot provide a finer structure of the mineral distribution. Hyperspectral remote sensing, also known as imaging spectroscopy, yields continuous spectral signatures and narrow bandwidth and hence has the great potential to identify the minerals on the Moon. Three lunar satellites recently launched by Japan, China and India all have hyperspectral instruments including SP on SELENE, IIM on Chang'E-1, and M³ and HySI on Chandrayaan-1. Relative to the multispectral data, hyperspectral instruments can acquire the exact absorption center of lunar minerals with its continuous and high resolution spectra. Knowing the global distribution of the absorption band center of the mafic minerals on the Moon can contribute to lunar scientific research. However, until now there is still no global absorption center map. IIM does not cover the absorption peak of the mafic minerals completely due to its narrow spectral range. In this study we have explored the method of extending the spectral range of IIM to acquire the absorption center of the lu-

nar mafic minerals. The global absorption center map of the mafic mineral of the Moon is produced via our method and the calibrated IIM data, and some of the implications of the global absorption center map are discussed. Our method is also useful for other instruments which are limited by their narrow spectral range due to the natural response feature of silicon detector. All the processes are accomplished using the Lunar Geochemical Mapping System (LGMS v1.0), designed with IDL specifically for CE-1 optical images by our group.

2 IIM data preprocessing

The first Chinese lunar satellite, Chang'E-1, was launched on Oct 24, 2007 and ended its 16-month mission by impacting the Moon on Mar 1 2009. The Interference Imaging spectrometer (IIM) which covers wavelengths from 480 to 960 nm with 32 channels onboard Chang'E-1 is aimed to acquire the composition of the Moon. The instrument is a Sagnac-based pushbroom Fourier transform imaging spectrometer and maps the lunar surface with a swath of 25.6 km from the polar orbit of 200 km altitude. Figure 1 shows the sketch map of IIM data cube over the Aristarchus area.

IIM has covered 84% of the area between south and

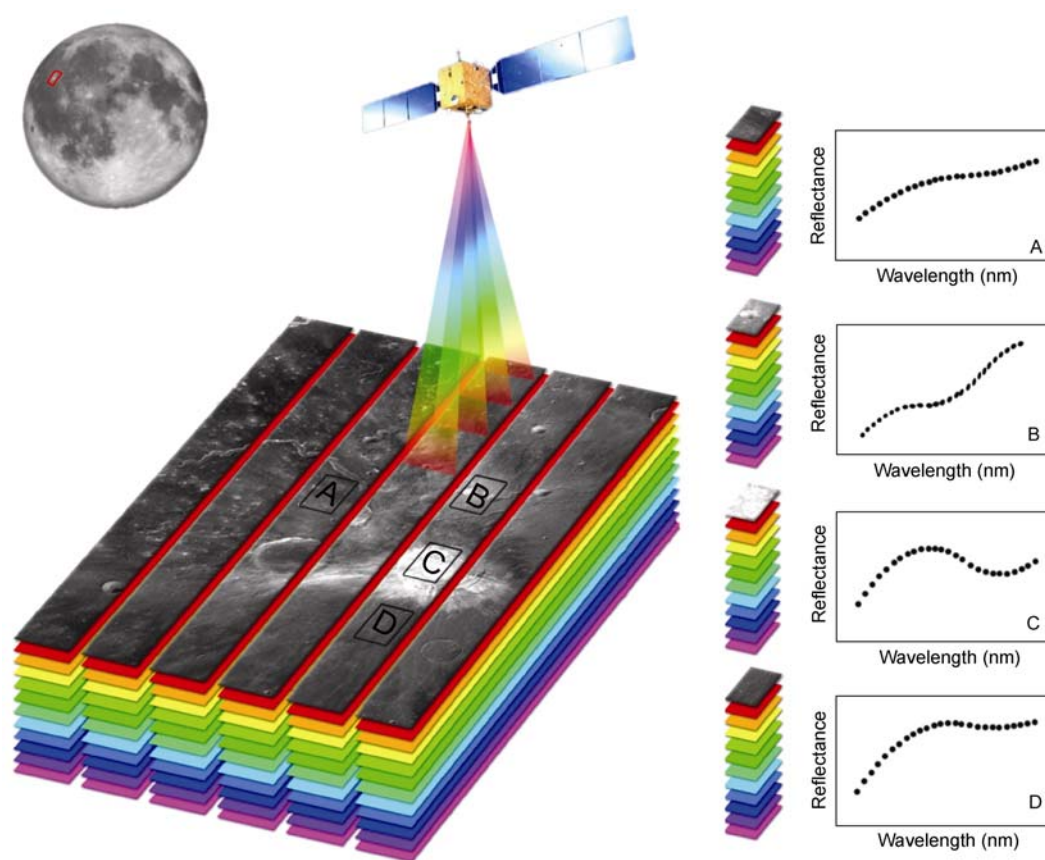


Figure 1 Sketch map of the IIM data cube over the Aristarchus area.

north latitude 70° during its one-year mission. All the data has been received, processed, archived and distributed by the Ground Segment for Data, Science and Application (GSDSA) of China's Lunar Exploration Program. We acquired 575 orbits IIM data from the GSDSA. A total of 278 orbits with good quality from all the 575 orbits are used in this study by checking the data quality (Figure 2). The IIM data is systematically processed in several steps. However, it should be processed further before it is used. Figure 3 is the flowchart of IIM processing and application used in this study. In the following we will describe some processes in detail.

2.1 Wavebands inspection and selection

Accurate data are the basis for scientific research. Some bands of IIM data are abnormal or have very low SNR. These bands cannot be used for the information extraction and hence they should be eliminated before use. The inspection of the IIM bands is the first step for preprocessing IIM data. Because IIM does not have on-board calibration system, the credibility of IIM band properties is checked by comparing modeled spectra with measured IIM spectra. Figure 4 shows the comparison of the IIM radiance measured from an area close to the Apollo 16 landing site and the radiance modeled for the site based on the Apollo 16 soil reflectance, viewing and illumination angles and solar irradiance spectrum. As shown in Figure 4, some bands of measured IIM data are inconsistent with the modeled data, especially for the first and last bands. Therefore, these bands will be eliminated before they are used. By a comprehensive consideration of SNR and the largest band number, bands 1–10 and 32 are eliminated and only the

remaining 11–31 bands are used in the following study.

2.2 Denoising of the image

In this study denoising of the image includes three steps: bad lines repair, bad points repair and destriping. The bad lines in IIM data appear as dark or bright vertical lines. These vertical lines have much lower or higher values as compared to their immediate neighboring lines. The bad points in IIM data appear as very bright pixels. The difference between a bad line and a bad point is that for the bad point abnormal pixel is singly and discretely distributed in the image while for the bad line the abnormal pixel is distributed in the line. Any bad line, bad point, and stripe lower the quality of the image and what's more, they affect the spatial filter for future processing. They must be preprocessed prior to the derivative calculation for the IIM data.

A method named Pixel Gray-scale Slope Threshold (PGST) was used to detect any possible bad line. Firstly, the gray-scale slope S of each pixel was calculated:

$$S_{i,k} = \frac{(DN_{i-1,j,k} + DN_{i+1,j,k} - 2 \cdot DN_{i,j,k})}{|DN_{i-1,j,k} - DN_{i+1,j,k}|}, \quad (1)$$

where DN denotes the value of each pixel, and i, j, k denote the column, row, and band number of the pixel. S describes the reflectance difference between a pixel and its left and right neighboring pixels. If the absolute value of S is relatively small, it indicates that the change of reflectance at this pixel is smooth. However, if the absolute value of S is very large, it indicates that this pixel is a sudden change compared to its neighbors and thus this pixel is likely to be an abnormal pixel. Two kinds of thresholds, positive and

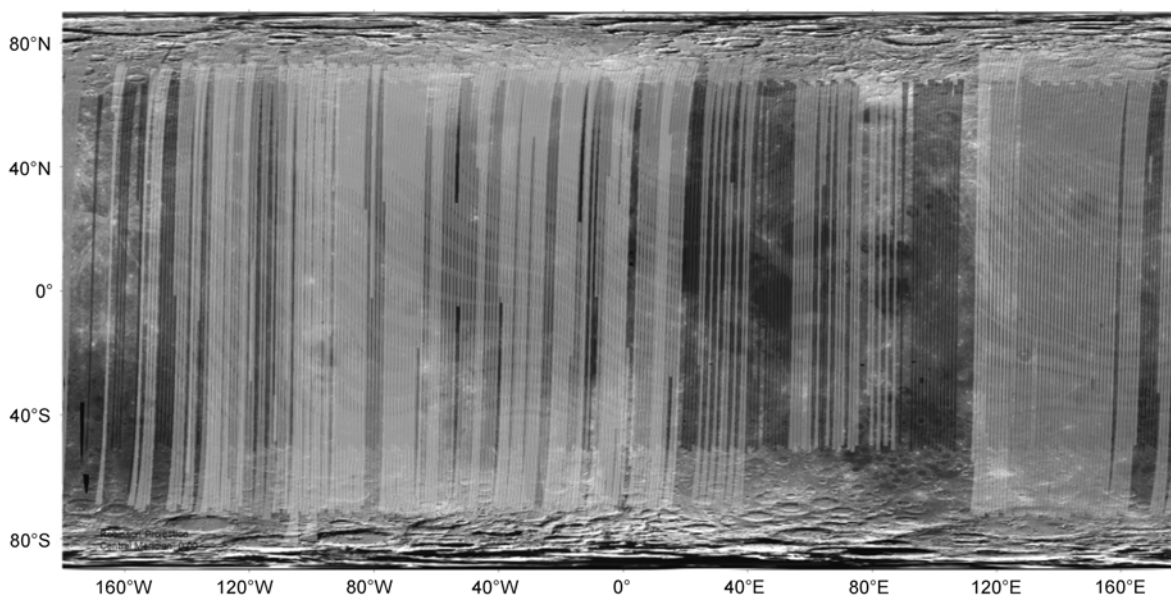


Figure 2 The sketch map for the location of IIM data used in this study.

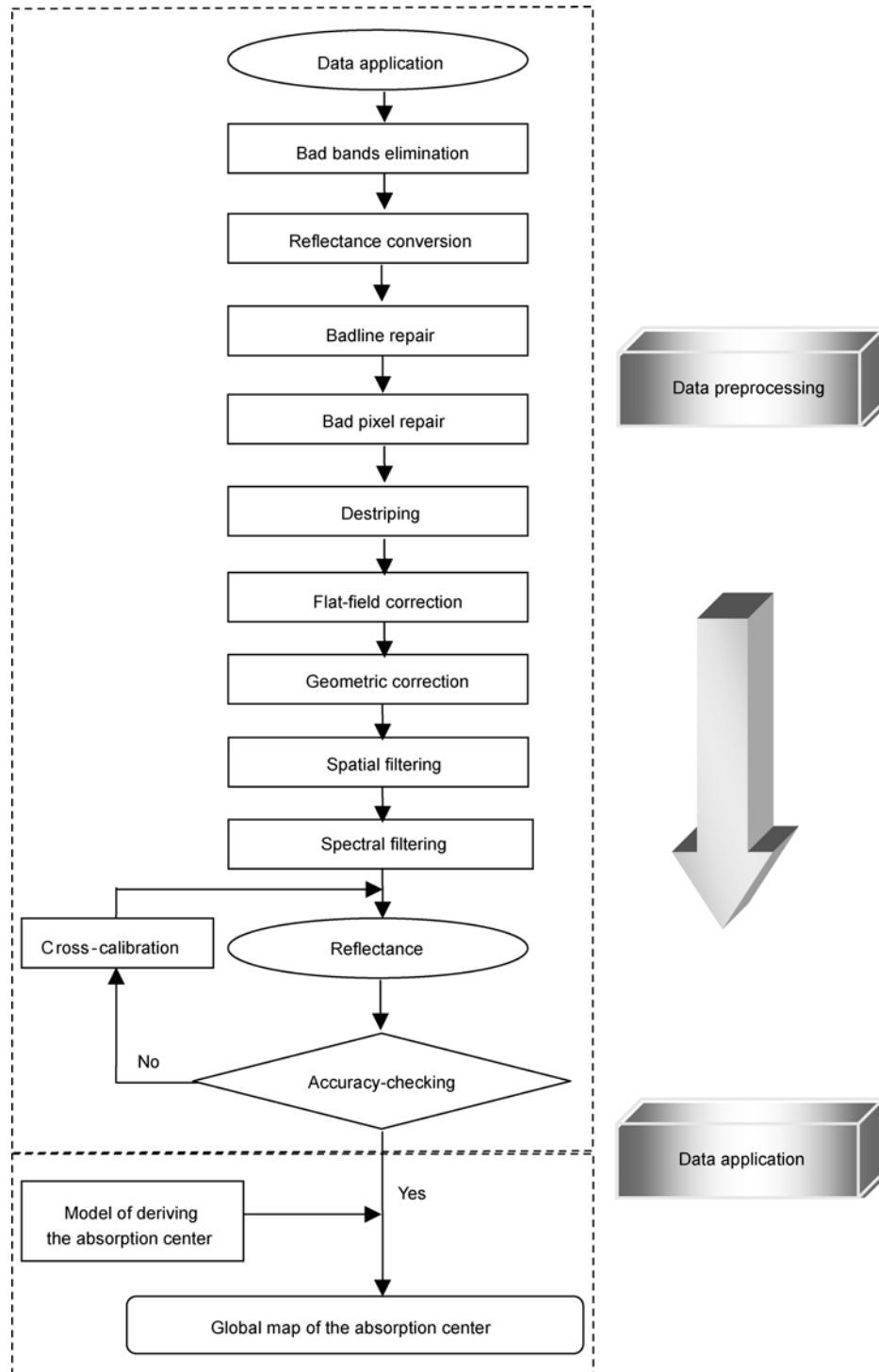


Figure 3 Flowchart of IIM processing and application in this study.

negative, were set because IIM has bright and dark bad lines. If $S > \text{positive threshold}$ or $S < \text{negative threshold}$, then the pixel was labeled as a candidate abnormal pixel.

Secondly, the percentage of abnormal pixels P in each column was calculated:

$$P_{i,k} = \frac{Sb_{i,k}}{St_{i,k}}, \quad (2)$$

where $Sb_{i,k}$ and $St_{i,k}$ denote the number of abnormal pixels and the number of all pixels in column i for band k .

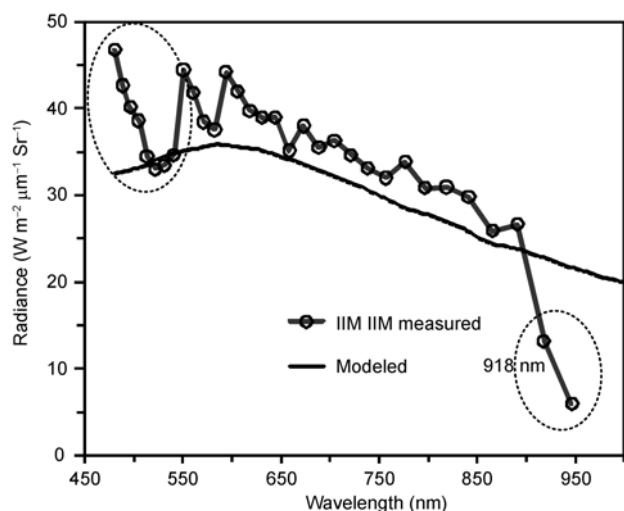


Figure 4 Comparison of an IIM measured and modeled spectrum for the Apollo 16 soil.

The threshold for badline flag number percentage (BFNP) was set to judge whether the column is the bad line or not. If $P > \text{BFNP}$, then the column was marked as bad line.

After the bad line was detected with the two thresholds described above in formula (1) and (2), the bad line was repaired by replacing its value with the average value of its immediate left and right neighboring pixels:

$$DN_{i,j,k} = \frac{DN_{i-1,j,k} + DN_{i+1,j,k}}{2}. \quad (3)$$

For the bad points, which are singly and discretely distributed in the IIM image, the pixel was compared with its immediate eight neighboring pixels, and the threshold was set to judge the bad point. After the bad point was detected, it was repaired by replacing its value with the average value of its immediate eight neighboring pixels.

Vertical stripes are very common in the push-broom instruments (e.g. IIM, Hyperion) due to the factors such as detector nonlinearities, temperature effects, movement of the slit with respect to the focal plane, and calibration of some detectors with significantly modified gain and offset. Several methods such as histogram equalization, minimum noise fraction (MNF) rotation, wavelet transform, Fourier transform and texture filtering can be used to remove the vertical stripes. By several experiments in this study we used global histogram equalization to remove the striping:

$$I' = I \cdot d_{\text{all}} / d_{\text{column}} + m_{\text{all}} - m_{\text{column}} \cdot d_{\text{all}} / d_{\text{column}}, \quad (4)$$

where I is the original reflectance value of a pixel. d_{all} and d_{column} are the standard deviations of the reflectance of the band and the column in which the pixel is located. m_{all} and m_{column} are the mean of the reflectance of the band and the column in which the pixel is located.

Our bad line and bad point detection algorithm works well for most bands. The results show that almost all the

bands of IIM have bad lines, especially for the shorter and longer bands. The denoising process (bad line repair, bad point repair, destriping) significantly improves the visual effect of noisy bands. Examples of the processing results are shown in Figure 5. It can be seen that the image quality was significantly improved visually after the correction. A close inspection of the spectral dimension shows the spectral shape remains unchanged (unshown data). The MNF analysis also shows that both the broad low-frequency effect and the local stripes have been reduced and the image is clean (unshown data).

2.3 Flat-field correction

Besides the bad line and vertical stripe, non-uniformity of sensor response, i.e., flat-field response, is another factor which significantly affects IIM application as well as image quality. The heterogeneity of the sensor response can produce very different mineral information for the left and the right of the same horizontal line even if they share the same composition. Therefore, the heterogeneity of the sensor response must be corrected before the data are used for geological research.

The optimal method for flat-field correction is to determine the heterogeneity function with well defined surface in the laboratory. According to the present situation (only from the standpoint of data) and the incapability of the synchronous measurement of reflectance, we used the method named reflectance normalization to acquire the flat-field correction factor. A detailed description of the flat-field correction for IIM data can be found in ref. [7].

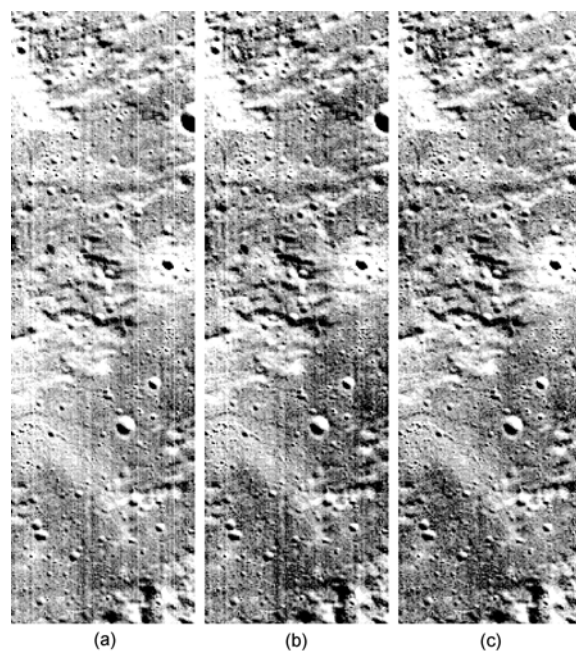


Figure 5 Reflectance of the original IIM 571 nm (a), bad line repaired (b) and destriped IIM data (c).

3 Acquiring the absorption band center

To investigate the method of extending the spectral range of IIM data to acquire the absorption center of the mafic minerals, we used the simulated spectra and the measured data in the laboratory and the Earth-based telescope. They covered simplified and complex, modeled and measured, in situ and remotely sensed system, respectively.

3.1 Modeling of mineral mixtures

The modeling method was first used to investigate the feasibility of extending the spectral range of IIM data to acquire the absorption band center of mafic minerals. The lunar surface for which remotely sensed reflectance spectra are measured is composed of an assemblage of fine-grained

intimately mixed minerals and alteration products. It is well known that an intimate mixture of minerals produces a spectral reflectance that is a nonlinear combination of the reflectance spectra of the individual components [8–10]. In this study the reflectance of the mixed system was calculated using the Hapke model [10] to linearize the mixing system. In this study for the first step the simple case was performed and hence only pure mineral mixture was modeled while the glass, agglutinates, and submicroscopic iron were not considered. For the calculation the mineral fractions in the mixture system were obtained from the lunar soils studied by LSCC [11]. Table 1 shows the modal abundance of minerals used in the simulation, which spans the KREEP, Highland and Mare terrane.

The modeled reflectance spectra are shown in Figure 6(a). The spectra of which are significantly different from others

Table 1 Modal abundance of minerals used for the simulation in this study

	KREEP		Highland		Mare			
	12001	12030	14259	61221	70181	71501	71061	79221
Olivine	4.2	3.7	1.4	2.0	3.8	3.4	4.5	3.4
Clinopyroxene	8.34	8.33	2.16	2.09	4.71	7.59	7.09	5.06
Orthopyroxene	2.24	2.86	3.72	1.82	1.2	1.47	1.32	1.64
Pigeonite	7.36	10.18	3.18	1.43	2.57	4.61	4.07	2.86
Ilmenite	1.8	3.2	1.2	0.3	6.7	9.7	9.7	6.0
Plagioclase	13.9	14	15.4	59.4	18.3	19.8	15.2	16.0

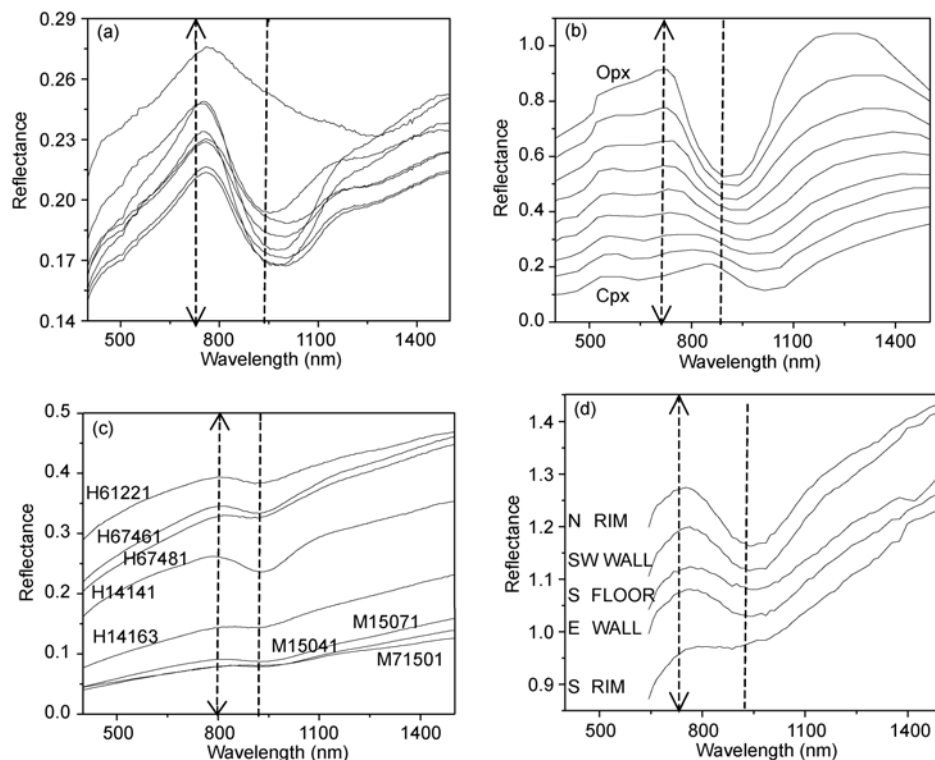


Figure 6 (a) Reflectance spectra of mineral mixtures calculated using the bidirectional reflectance equations of Hapke (1981) to linearize the mixing system. Mineral mixture data were originally from the eight LSCC. (b) Mineral mixture of the orthopyroxene-clinopyroxene series originally from [12]. They are displayed from bottom to top with an increasing orthopyroxene fraction and a 5% offset in reflectance between each successive spectrum. (c) Laboratory spectra of the eight LSCC lunar soils. (d) Reflectance spectra for the Aristarchus crater obtained with Earth-based telescopes (scaled to unity at 1020 nm and offset for clarity) [13].

were calculated using the mineral fractions of 61221. Its plagioclase is much larger than that of others (Table 1). Figure 7(a) shows the relationship between the stagnation point and the absorption center for all samples except for 61221. They are highly positively correlative with a correlation coefficient of 0.98. Sample 61221 was not shown in Figure 7(a), for its absorption band center is very long (1267 nm). However, its stagnation point is also the longest (767 nm) among all the samples, which suggests that it is also consistent with the positive correlation between the stagnation point and the absorption center.

3.2 Simple mineral mixtures

After the theoretic simulation, we used the measured reflectance spectra of a simple system, and two mineral mixtures, to investigate the implications of the stagnation point. Figure 6(b) shows the digitized reflectance spectra of orthopyroxene-clinopyroxene mixtures from the work of [12]. The simple system shows more clearly than the modeled for several mineral mixtures (Figure 6(a)) for the relationship between the stagnation point and the absorption center. As the absorption center increases with the increase of clinopyroxene fractions, the wavelength of the stagnation point also increases. The positive correlation between the stagnation point and the absorption center can also be found in Figure 7(b).

3.3 LSCC lunar soils

After the investigation with the simple system, next we test the relationship with the true lunar soils. Figure 6(c) shows the lab reflectance spectra of the eight lunar soils: 14141, 14163, 61221, 67461, 67481 from the highland and 15071, 15041, 71501 from the mare. They were obtained from the RELAB spectral database [11]. Although the absorption of the lunar soils is not as strong as that of the mineral mixtures, it can be seen in Figure 7(c) that the positive correlation discussed above is very high.

3.4 Telescopic spectra

In the end we used a much more complicated system, Earth-based telescopic spectra, to further investigate the implications of the stagnation point. Previous studies showed that the Aristarchus crater is of geological complex and spectral diversity with Olivine, CPX, OPX and Plagioclase existing within this crater [14–18]. We used the telescopic spectra of this crater because 1) it has a largely compositional diversity; 2) many spectra with high quality have been acquired for this crater; 3) it is new and the spectra are relatively less affected by the space weathering. The telescopic spectra obtained for the northern rim, the southwestern wall, the southern floor, the eastern wall and the southern rim are shown in Figure 6(d). Although the mix-

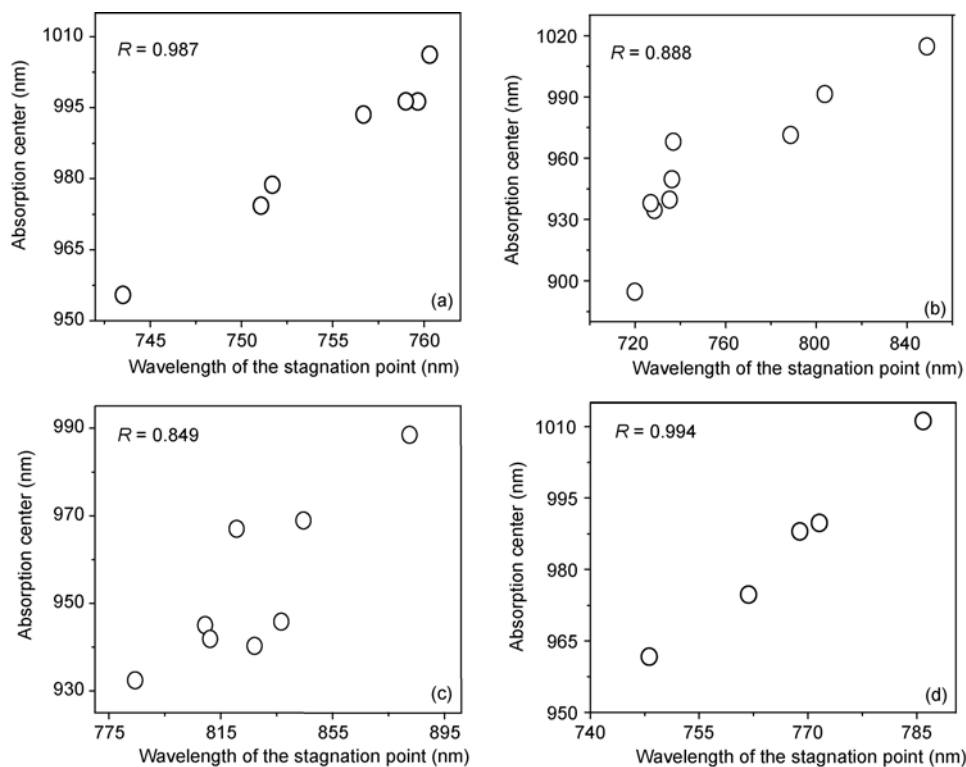


Figure 7 The relationship between the absorption center and the stagnation point derived from the same data as in Figure 6. Generally they are positively correlative. The linear correlation coefficient is also shown in each plot.

ture system of the Earth-based telescopic spectra is more complicated, the correlation discussed above does not fall. As can be seen in Figure 7(d), the stagnation point is highly correlated with the absorption center. The correlation coefficients are the highest among the four data sets.

4 Global absorption center map of the mafic minerals on the Moon

The four investigations performed above gave the consistent results, i.e., the stagnation point is positively correlated with the absorption band center. This indicates that although the spectral range of IIM does not cover the absorption peak of the mafic mineral completely, the absorption center could be mapped with this correlation and the stagnation point derived from the IIM data. Figures 8 and 9 show the global maps of the 865-nm and color-coded absorption band center with an Orthographic and Equirectangular projection, respectively. Some pixels do not have a stagnation point within the band range of IIM, especially for highland anor-

thositic rocks, pyroclastic deposits and impact melts. The values of these pixels without a stagnation point are assigned 0 (black pixels in Figures 8 and 9). In the following we will verify whether the map of the absorption band center is right or not and discuss its implications.

The olivine composition of the central peaks of Copernicus has been observed by the Earth-based telescopic spectra [19,20] and Clementine data [21], who found that the three central peaks of Copernicus have different olivine contents, with the easternmost central peak (CP2) being the richest in olivine. Figure 10 shows that from the right to the left (CP2 to CP3 to CP1), the absorption band center of Copernicus crater moves to shorter wavelengths, which means that olivine is the richest in the CP2 and poorest in the CP1. Our results are in good agreement with previous observations but provide a much finer structure, which testifies to the accuracy of detection and our process method of this instrument.

Moreover, we further inspected the absorption band centers of Mare Orientale, Aristarchus, and Tycho which are not very old. The minerals of these fresh craters are consis-

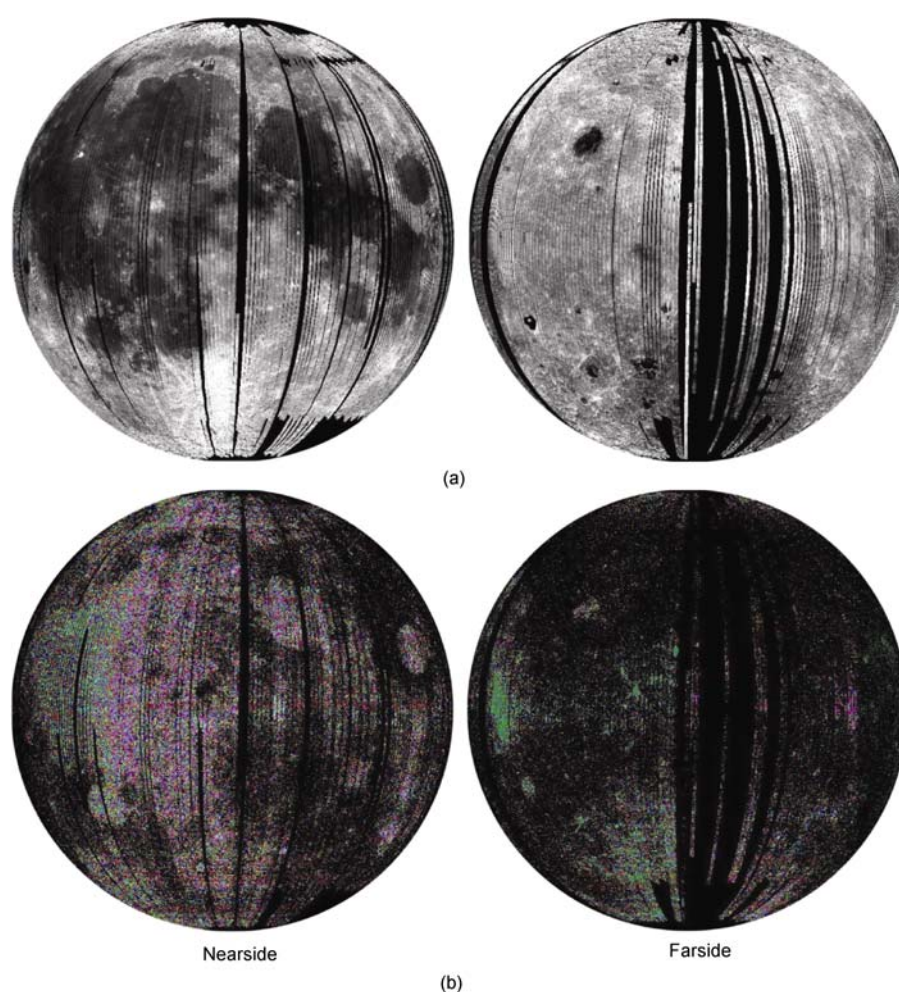


Figure 8 865-nm mosaic image (a) and color-coded map of the absorption band center (b) with an Orthographic projection.

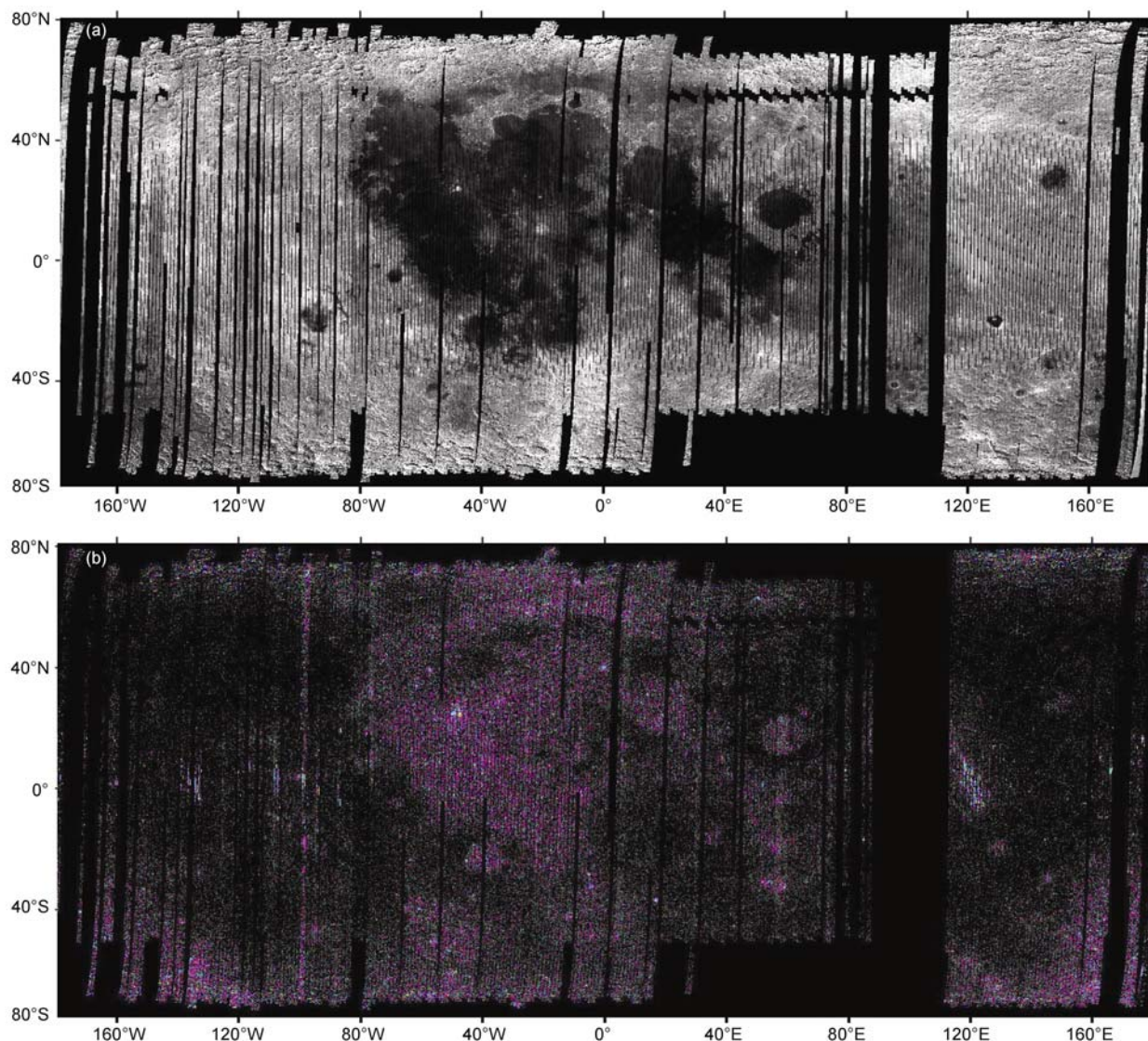


Figure 9 865-nm mosaic image (a) and color-coded map of the absorption band center (b) with an Equirectangular projection.

tent with previous research, which indicates the reliability of our global absorption center map. Although telescopic spectra have a high spectral resolution, the spatial resolution is limited. Clementine multispectral images are limited to its spectral resolution and cannot determine the specific absorption band center. Our results show the advantage of IIM with its high spatial and spectral resolution, e.g. the different pyroxene types of A, B and CP1 which had not been discriminated before were clearly identified.

In addition to the identification of lunar rocks and minerals, the map of the absorption band center can also contribute to finding small craters which have low contrast with their surroundings. For example, Point C near the rim of Copernicus crater is difficult to find in the brightness image (Figure 10) but can be easily shown in the absorption band center map. There is a very small crater within the mare basalts to the north of the central peak of Tsiolkovskiy cra-

ter. This small crater is almost as bright as the surrounding basalts and hence it's difficult to be seen in the brightness image. However, in Figure 10 it is very obvious in the map of absorption band center (red arrow in Figure 10). Its absorption center is around 960 nm, which indicates that its composition is mostly high-Ca pyroxene. This is consistent with the fact that mare basalts are mostly high-Ca pyroxene. The FeO and TiO_2 of this crater is approximately the same as the adjacent mare deposits, while its optical maturity parameter is much higher than that of the adjacent mare deposits (Figure 11(d)), which suggests that this small crater is new. In contrast to this small crater, the very bright point to the left of the crater (left arrow in Figure 11) is easy to be identified as the crater according its high brightness and morphology. However, its absorption band center is very long, which is inconsistent with that of the mare basalts. Therefore, we cannot arbitrarily think that it is one crater.

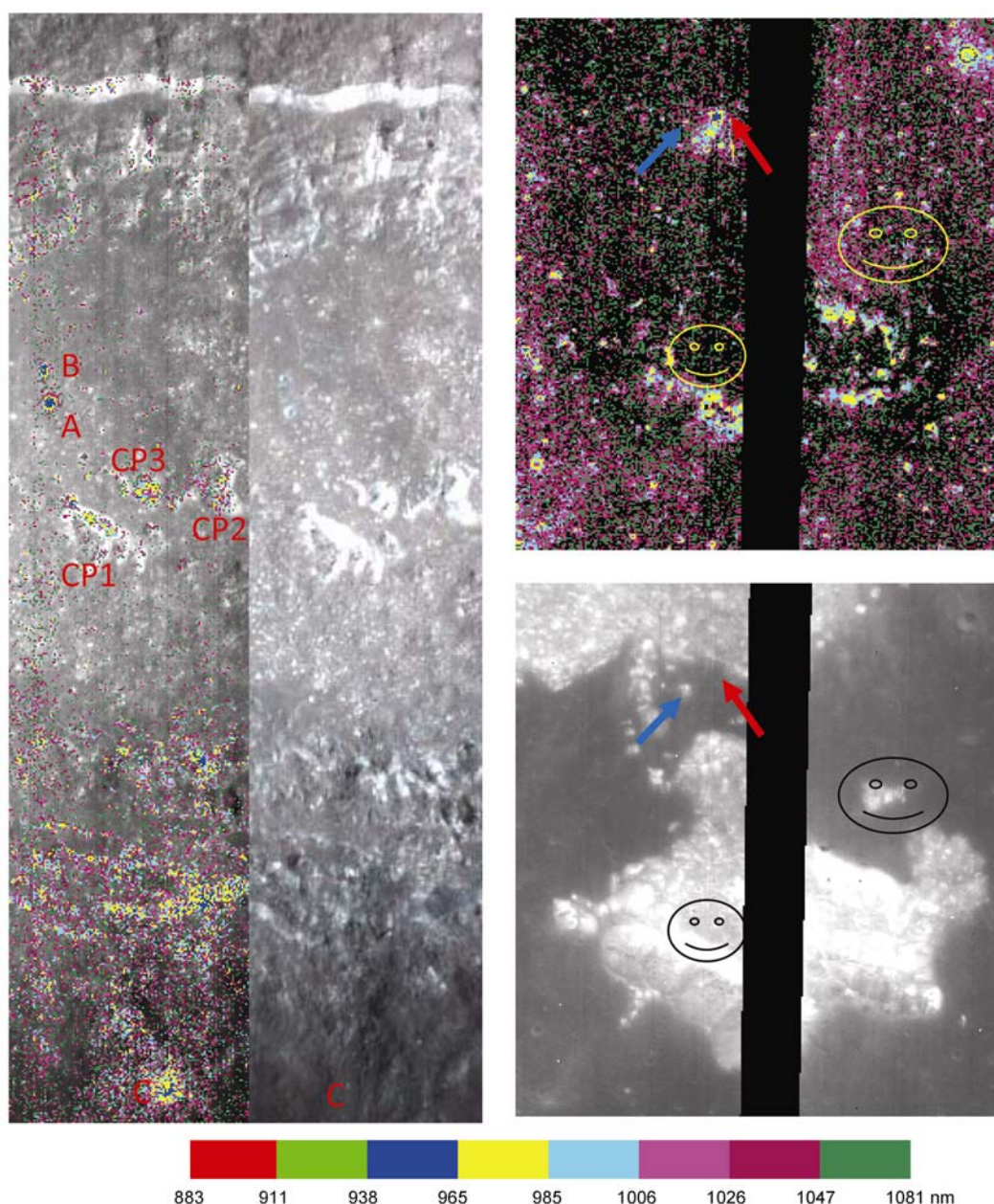


Figure 10 Map of the absorption band center for Copernicus (left) and the Tsiolkovskiy crater (right).

The FeO and TiO₂ of this point are much lower than that of the adjacent mare deposits (Figures 11(b) and (c)). We think that this point is the anorthosite central peak which was not annihilated by the mare basalts flow.

The viewing and illumination geometry can affect the reflectance of the lunar surface. The illuminated face and shadowed face of one crater show different reflectance, though they have the same compositions (Figure 12(a)). As shown in Figure 12(b), the absorption center is concentric, which means that our method is insensitive to the topographic effect, and further indicates that the minerals identified with our method for both the illuminated and shadowed faces are reliable. The absorption band center has a concentric distribution with longer wavelength centers outside the

crater. This indicates the importance of the spectral interpretation, i.e., the spectral mixture between the fresh material and the surrounding substrate. Figure 12 also suggests that besides helping identifying lunar minerals, the global map of the absorption center may have other implications. For example, it may be used to assess the mixture between the ray and the surrounding substrate. In future studies we will explore its implications and potential applications.

5 Conclusions

The minerals and rocks on the Moon are necessary for understanding the origin and evolution of the Moon. Remote

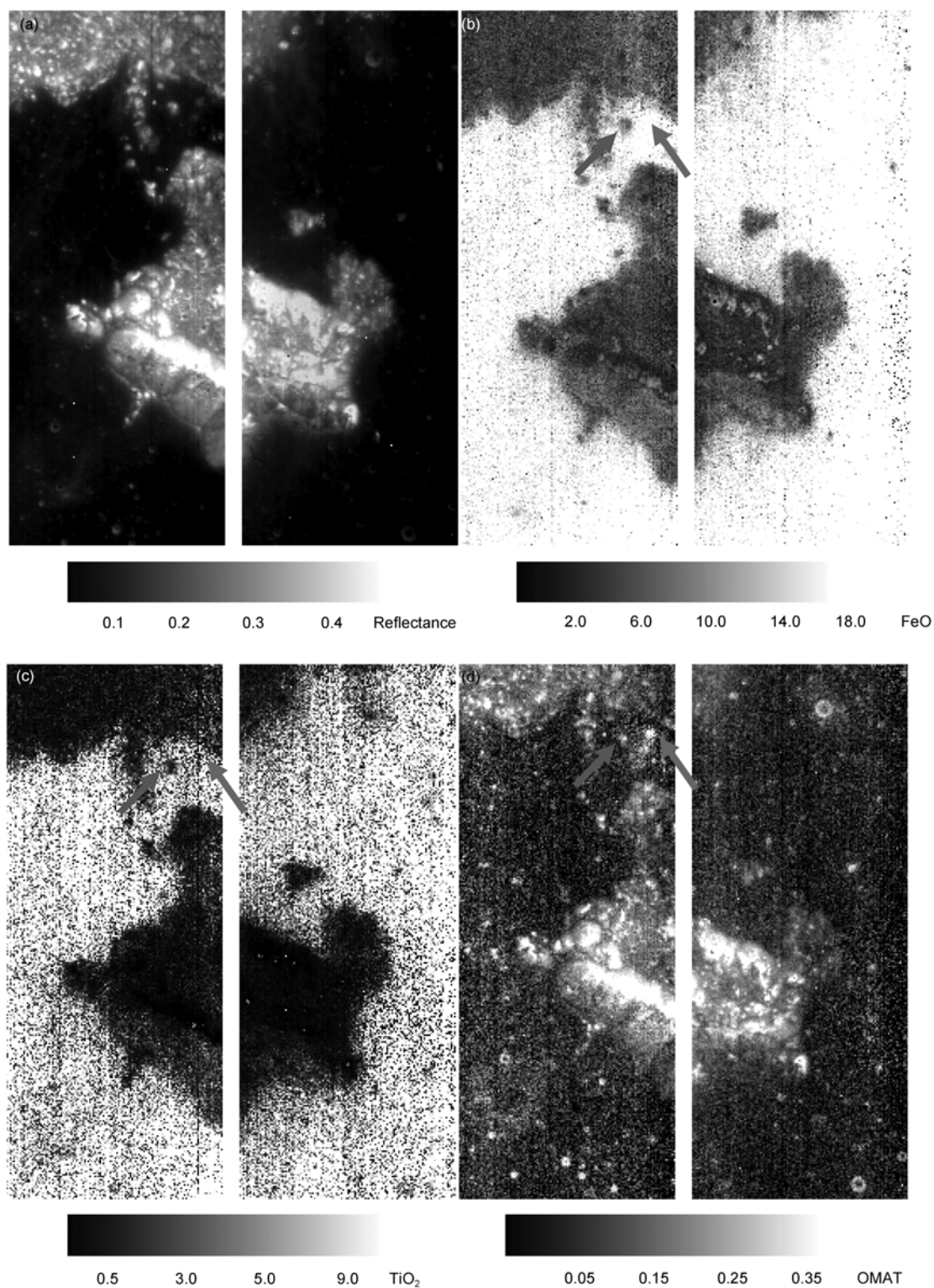


Figure 11 (a) IIM 750 nm image showing the Tsiolkovskiy crater. North is indicated by the top. (b) FeO map derived from IIM data. This image stands for the same area as the 750 nm image shown in (a). (c) TiO₂ map produced from IIM images. The image stands for the same area as the 750 nm image shown in (a). (d) Optical maturity parameter image (OMAT) produced from IIM images. Brighter tones indicate lower maturity (fresher material).

sensing technology provides a global perspective that the sample collection alone cannot. As one hyperspectral instrument, IIM can acquire continuous and high resolution

spectra of the Moon, and consequently can acquire the precision wavelength of the Moon. The global map of the absorption band center was first produced based on the cali-

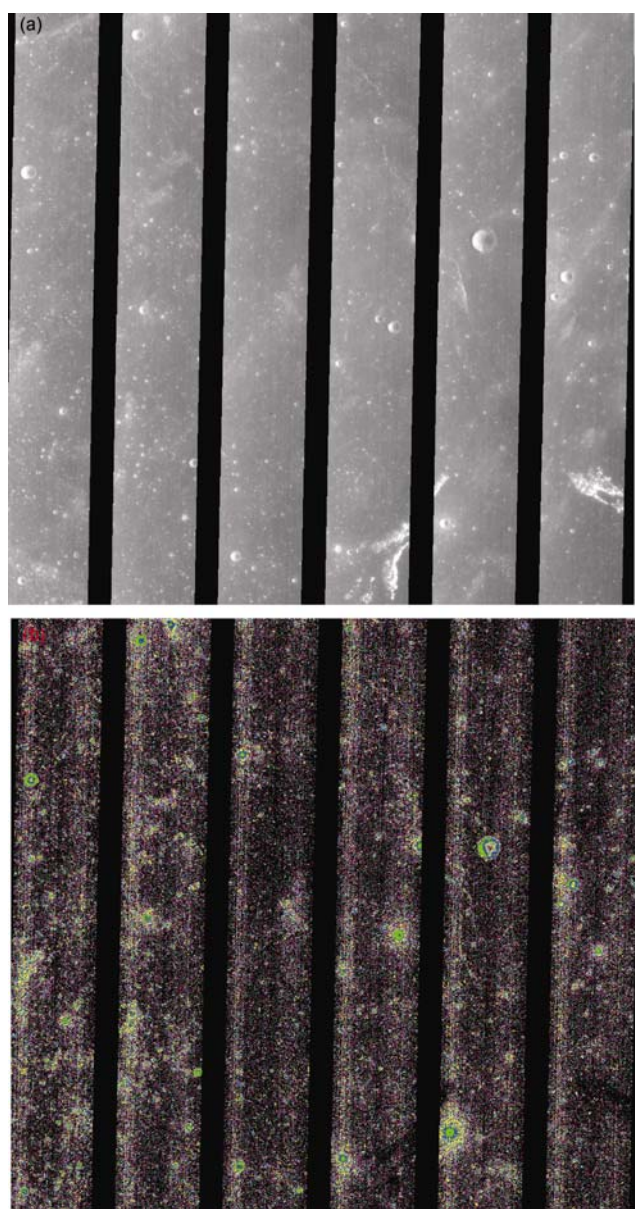


Figure 12 IIM 891 nm image (a) and the absorption band center of the same area (b).

brated IIM and the model based on the relationship between the stagnation point and the absorption center.

However, it should be noted that all the minerals of the Moon and other planets exist in the form of mixture. Due to a narrow spectral range of IIM, the individual absorption band of each mineral cannot be acquired by means of deconvolution. In spite of this, the consistent results for some crater from previous researchers indicate the effectiveness of the global absorption center map. Moreover, the global map of absorption band centers may have other significance needed further research.

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